

UNIVERSITÀ DI PISA



Facoltà di Ingegneria

Corso di Laurea Specialistica in Ingegneria Meccanica

MISALIGNMENT PROBLEMS FOR A CONTINUOUS SCANNING LASER DOPPLER VIBROMETER FOR CYLINDRICAL STRUCTURES

Tesi di laurea

Relatori:

Prof. Ing. Leonardo Bertini

Prof. David J. Ewins

Prof. Ing. Marco Beghini

Candidato:

Luca Massei

Sessione di Laurea del 13/06/2007

Anno accademico 2006/2007

Consultazione consentita

*A Paola e ai miei genitori
che mi hanno sempre sostenuto*

ABSTRACT

This thesis has been developed at Imperial College, London. The aim is the definition of a model that evaluates the alignment of the components of a laser Doppler continuous scanning vibrometer in order to assess the tracking errors of the laser spot. A series of measurement tests on the system has been carried out to highlight the effect of misalignment of the system components on the measurement output. A geometrical model of the laser tracking error related to the orientation parameters of the system has been realised: the model has been checked with a CAD simulation and measurement tests on the structure. Moreover a sensitivity analysis has been performed to weight the tolerance limits for the alignment of the system components. The ideal path and the misaligned path are simulated over the finite elements model and compared using the “Modal Assurance Criterion” in order to state a threshold for the measurement accuracy that considers also the dynamic behaviour of the measured structure.

SOMMARIO

La presente tesi è stata svolta presso l'Imperial College London. L'obiettivo è la definizione di un modello di calcolo che valuti i problemi di allineamento per i componenti di un sistema laser ad effetto Doppler a scansione continua per la misura delle vibrazioni. Sono state eseguite misurazioni sull'attrezzatura in modo da evidenziare l'effetto del disallineamento delle componenti del sistema sulla misura. Si è realizzato un modello geometrico dell'errore di puntamento del laser in relazione ai parametri di orientamento dei vari componenti del sistema: tale modello è stato validato tramite una simulazione CAD e misure sul sistema. E' stata quindi eseguita un'analisi di sensibilità i cui risultati sono stati utilizzati per scalare le specifiche da imporre ai vari parametri di orientamento. La traiettoria ideale e quella dovuta ai disallineamenti del sistema vengono simulate sul modello agli elementi finiti e i risultati vengono comparati utilizzando il "Modal Assurance Criterion", in modo da stabilire una soglia per l'accuratezza che consideri anche il comportamento dinamico della struttura misurata.

ACKNOWLEDGEMENTS

I thank Professor D.J. Ewins for his support during my work and because he offered me the possibility to spend some months in the stimulating environment of the Dynamics group in the Department of Mechanical Engineering at Imperial College London.

I am also grateful to Professor L. Bertini and Professor M. Beghini for helping me through the set up of this experience and also for the suggestions to improve the organization of this work.

Special thanks to Dr. C. Schwingshackl for cooperating to this work and for the precious help he has given me, introducing me to the experimental aspects of the vibration measurement. Thanks also to Mr. D. Di Maio and Mr. R. Ribichini for their friendship and their constant care during the period spent at Imperial College.

I acknowledge the financial support of “Programma Leonardo” managed by University of Pisa which allowed me to attend to this experience.

CONTENTS

LIST OF FIGURES	X
LIST OF TABLES	XIII
1 INTRODUCTION	1
1.1 Background	1
1.2 Objectives of the thesis	3
1.3 Literature review	3
1.4 Contents of the thesis	4
2 THE LASER DOPPLER VIBROMETRY	6
2.1 Introduction	6
2.2 Scanning Laser Doppler Vibrometry	11
2.3 Continuous Scanning Laser Doppler Vibrometry	13
2.3.1 Uniform speed line scan	15
2.3.2 Sinusoidal speed line scan	17
2.4 Use of the measurements: the model updating	19
2.4.1 Model verification and correlation	20
2.4.2 Model updating	21
3 THE “LIGHTHOUSE” METHOD OF CONTINUOUS SCANNING LASER DOPPLER VIBROMETRY	23
3.1 Description of the measurement test rig	23
3.1.1 Measurements on cylindrical structures	23
3.1.2 The “Lighthouse” solution	24
3.1.2.1 Components of the rig	25
3.1.2.2 Data acquisition system	27
3.1.2.3 Data post processing	29
3.2 Measurement tests on the rig	30
3.2.1 Set up of the rig	30

3.2.1.1 The measured structure	30
3.2.1.2 Alignment procedure	31
3.2.2 ODS reconstruction with aligned system	33
3.2.2.1 Research of the frequencies	34
3.2.2.2 ODS reconstruction	38
3.2.3 ODS reconstruction with misaligned system	39
3.2.4 Effect of the mirror speed on the velocity response	43
4 MATHEMATICAL MODEL FOR THE “LIGHTHOUSE CSLDV”	
ALIGNMENT	45
4.1 Introduction	45
4.2 Geometrical model for the alignment	46
4.2.1 Alignment between rotating mirror axis and measured structure	47
4.2.1.1 Structure translations	48
4.2.1.2 Structure rotations	48
4.2.2 Alignment between rotating mirror axis and laser source	49
4.2.2.1 Laser translations	50
4.2.2.2 Laser rotations	51
4.2.3 Full model	52
4.3 Geometrical model validation	53
4.3.1 CAD simulation	53
4.3.2 Measurements on the structure	57
4.4 Sensitivity analysis	61
4.4.1 Axial error	62
4.4.2 Angular error	65
4.4.3 Sensitivity index	67
5. CALCULATION OF THE SPECIFICATIONS FOR THE RIG	69
5.1 Definition of tolerance limits for the orientation parameters	69

5.1.1 Use of the sensitivity analysis to weight the orientation parameters	70
5.1.2 Application to the present rig	73
5.2 Simulation of the misaligned path on the FE model	74
5.2.1 Research of the nodes along a path	75
5.2.2 Response of the FE model	78
5.3 Use of the Modal Assurance Criterion to evaluate the accuracy	80
5.3.1 The Modal Assurance Criterion	80
5.3.2 Assessment of the misaligned path using the MAC	82
5.4 Code implementation	83
5.4.1 Structure of the code	83
5.4.2 Tolerance limits evaluation	84
5.4.3 Error requirements loop	85
5.4.3.1 Node location and MAC evaluation	85
5.4.3.2 Error requirements raising	86
5.5 Example of application of the code	86
6 CONCLUSIONS	93
6.1 Overall conclusions	93
6.1.1 Measurement tests on the rig	94
6.1.2 Mathematical model	95
6.1.3 Specifications for the rig	95
6.2 Further work	96
REFERENCES	97
APPENDIX	99
A Matlab code	99
A.1 Lighthouse CSLDV	100
A.2 Parameters	100
A.3 Sensitivity	101

A.4 Sensitivity output	102
A.5 Minimum and fixed specifications	103
A.6 Error raising	104
A.7 MAC error	104
A.8 Tolerance limits	105
A.9 Tolerance iteration	105
A.10 Axial error	109
A.11 Angular error	109
A.12 Fixed and minimum specifications check	110
A.13 Tolerance output	112
A.14 Graphs	112

LIST OF FIGURES

2.1	Backscattering arrangement	7
2.2	Laser speckle	10
2.3	Velocity signal drop out	11
2.4	Rotating mirrors of a SLDV	12
2.5	Scanning LDV	12
2.6	Grid SLDV pattern	13
2.7	Continuous scanning LDV	14
2.8	Short scan length	14
2.9	Time domain signal – Uniform scan speed	16
2.10	Model updating flow chart	20
3.1	Scanning of cylindrical structures	24
3.2	Rotating cylindrical surface	24
3.3	Lighthouse CSLDV mirror	25
3.4	Signal drop out on hole	26
3.5	Lighthouse CSLDV rig	27

3.6	Data acquisition system	28
3.7	“Step sine sweep” control panel	28
3.8	“Constant sine axial scan” control panel	29
3.9	The Combustion Chamber Outer Casing on the engine	30
3.10	The Combustion Chamber Outer Casing model	31
3.11	Alignment between laser and mirror axis	32
3.12	Alignment between laser and CCOC axis	32
3.13	FE modal analysis for the 1 st mode	34
3.14	FRF for the 1 st mode	35
3.15	FE modal analysis for the 5 th mode	35
3.16	FRF for the 5 th mode	36
3.17	FE modal analysis for the 13 th mode	37
3.18	FRF for the 13 th mode	37
3.19	Velocity for the z=20mm cross section at k1.8Hz	38
3.20	ODS at 1 st mode frequency	39
3.21	Tilt of the laser source	40
3.22	Mobility amplitude aligned and misaligned at 1 st mode frequency	41
3.23	Mobility amplitude aligned and misaligned at 5 th mode frequency	41
3.24	Mobility amplitude aligned and misaligned at 13 th mode frequency	42
3.25	Velocity response for several spin speeds of the mirror	44
4.1	Coordinate system	47
4.2	Orientation parameters for the measured structure	48
4.3	Orientation parameters for the laser source	50
4.4	CAD model	54
4.5	Axial error simulation graph	56
4.6	Angular error simulation graph	56
4.7	Spot with aligned rig	58
4.8	Spot with misaligned rig	58
4.9	Measurement of the axial error on the structure	59

4.10	Axial error validation on the structure	60
4.11	Sensitivity index for θ_L - Axial error	63
4.12	Sensitivity index for θ_C - Axial error	63
4.13	Sensitivity index for x_L - Axial error	64
4.14	Sensitivity index for z_C - Axial error	64
4.15	Sensitivity index for θ_L - Angular error	65
4.16	Sensitivity index for θ_C - Angular error	65
4.17	Sensitivity index for ϕ_C - Angular error	66
4.18	Sensitivity index for x_C - Angular error	66
4.19	Sensitivity index for x_L - Angular error	67
5.1	Accuracy requirements	70
5.2	Location of the nodes along a path	75
5.3	Nodes enclosed in the square area	76
5.4	Node distance from the centre of the square area	76
5.5	Nodes localisation in the 3D situation	77
5.6	Nodes along the paths	78
5.7	Code general flow chart	83
5.8	Cylindrical structure	87
5.9	MAC index trend	90
5.10	Iteration of the tolerance limits evaluation (bisection method)	90
5.11	Axial error simulation	91
5.12	Angular error simulation	92

LIST OF TABLES

3.1	Errors for the velocity amplitude	42
3.2	Spin speeds of the mirror	43
4.1	Geometrical features	53
4.2	CAD simulation parameters	54
4.3	Simulation results – axial error	55
4.4	Simulation results – angular error	55
4.5	Geometrical features – Measurements on the structure	59
4.6	Axial error comparison	60
4.7	Sensitivity index for axial error	68
4.8	Sensitivity index for angular error	68
5.1	Tolerance limits for the present rig	74
5.2	Sensitivity index for axial error – Cylindrical structure	88
5.3	Sensitivity index for angular error – Cylindrical structure	88
5.4	Tolerance limits for the cylindrical structure	89